ANDREW CHUGG

THE PHYSICS OF NUCLEAR WEAPONS

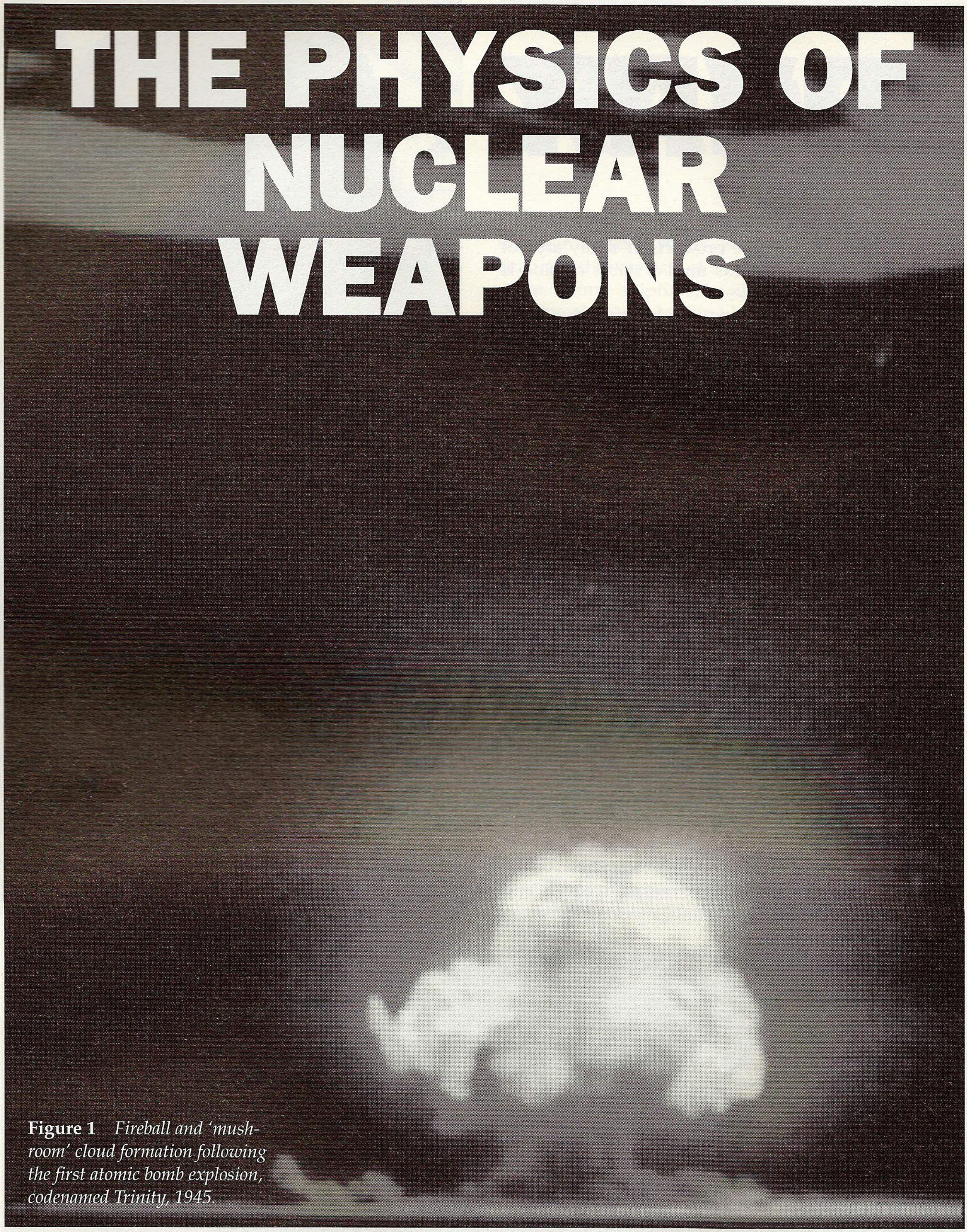


Figure 1 *Fireball and 'mushroom' cloud formation following the first atomic bomb explosion, codenamed Trinity, 1945.*

Last year saw the 50th anniversary of the first detonation of an atomic bomb. At the present time the world is in a period of nuclear proliferation, where more and more nations have the ability to develop their own atomic weapons. It is important to limit nuclear proliferation as far as is possible, because the probability of use increases as the number of nuclear powers rises. However, before you can take action to stop a proliferant nation's nuclear weapons programme, you first have to recognise the signs that one is under way. This article outlines the main technical features of nuclear weapons, which have now been published in open literature, in the belief that these facts should be known to future physicists, so they can more easily recognise cases where work they hear about or work they are being asked to perform might relate to a covert foreign nuclear weapons development programme.

It was 5.30 a.m. on 16 July 1945 at the Trinity test site north of Alamogordo, New Mexico, when daylight came early. A new sun flared in the desert plain, then reddened and heaved upwards, becoming a boiling purple mushroom cloud of radioactive debris, two miles high (Figure 1). A few seconds after the flash, the blast wave and the din of a gigantic explosion reached the onlookers. J. Robert Oppenheimer (Figure 2), Technical Director of the Manhattan Project (the code-name of the wartime atom bomb programme) and sometimes known as the 'Father of the Atom Bomb' quoted Hindu scripture: 'Now I am become Death, the destroyer of worlds.' This was the occasion, fifty years ago, when the awesome power of nuclear weaponry was first unleashed upon the Earth.

EINSTEIN AND ENERGY

An excellent place to begin to understand the physics of nuclear weapons is Einstein's most famous equation:

$$E = mc^2.$$

This equation associates energy E with mass m. The constant of proportionality is the square of the speed of light c. Because c is rather large (3×10^8 m s^{-1}), the equation suggests that there is a lot of energy associated with even a small amount of matter. In fact, one kilogram of matter contains 9×10^{16} joules of energy, which is roughly the amount of energy released by a hydrogen bomb. Chemical reactions, such as the combustion of petrol in car engines, free less than a billionth of the energy stored in the mass of the fuel, since they do not involve the atomic nuclei, where most of the mass is stored. However, in nuclear reactions the trick of releasing a large proportion of the bound-up energy becomes possible.

Figure 2 *Dr J. Robert Oppenheimer, who directed the making of the first atomic bomb.*

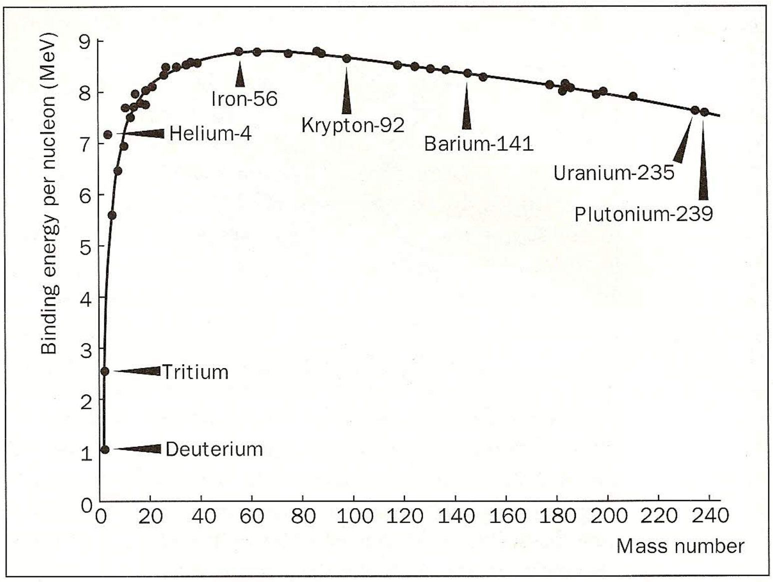


Figure 3 *Binding energy per nucleon as a function of mass number.*

FISSION AND FUSION

Two kinds of nuclear reaction may be used to release energy on a large scale. Fission is the splitting of heavy atomic nuclei into pairs of lighter nuclei, whilst fusion is the marriage of two light nuclei to form the nucleus of a heavier atom. When nucleons (protons and neutrons) come together to form an atomic nucleus, the nucleus is found to weigh less than the sum of the masses of the nucleons. The difference is the mass of the energy released when the nucleons combine (the so-called 'binding energy'). It turns out that the binding energy per nucleon, which is also known as the 'mass defect', varies for different sizes of nuclei. Figure 3 shows that the binding energy peaks for atoms about the size of iron. It can be seen that the fusion of light nuclei to form heavier ones generally increases the average binding energy per nucleon. The same is true of the fission of nuclei that are much heavier than iron.

Certain kinds of heavy nuclei such as uranium-235 and plutonium-239 split very readily when hit by a

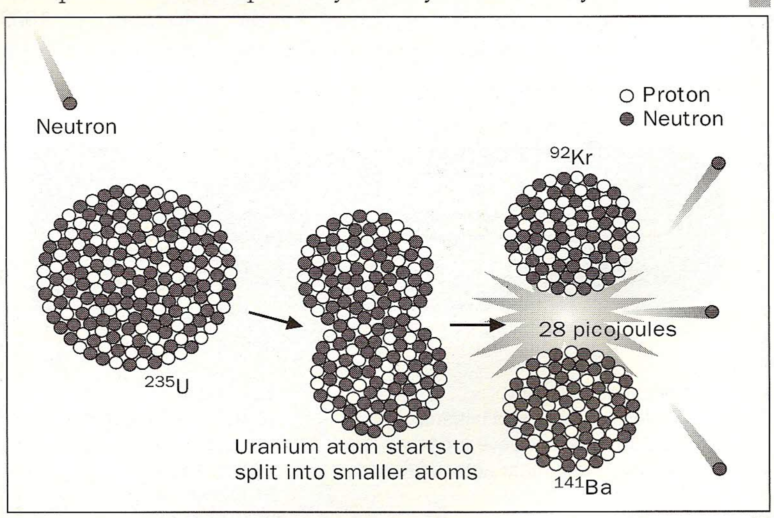


Figure 4 *Nuclear fission of uranium-235. Uranium atom splits (fissions) into lighter atoms — in this case, barium and krypton, releasing 3 spare neutrons plus 28 picojoules of energy (1 pJ = 10^{-12} J).*

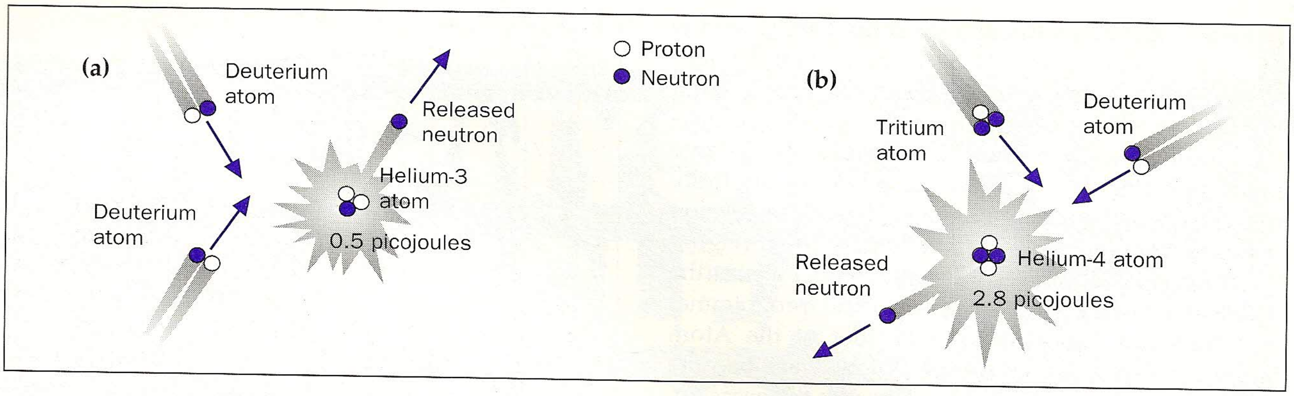


Figure 5 *Two examples of fusion reactions. (a) Two deuterium atoms collide and fuse into a heavier atom of helium-3. This reaction releases a neutron and about 0.5 picojoules of energy. (b) One tritium atom collides with a deuterium atom and fuses into a heavier atom of helium-4. This reaction releases a neutron and about 2.8 picojoules of energy.*

free neutron. As well as the two lighter daughter nuclei, these fissions tend to produce two or three further free neutrons. If, on average, more than one of these product neutrons goes on to cause a further fission, then successive generations of fissions involve exponentially increasing numbers of atoms in a nuclear chain reaction (Figure 4). A chain reaction can very quickly lead to the fission of a large fraction of the atoms in a block of uranium or plutonium.

If the average number of neutrons from each fission which go on to initiate further fissions is k (called the k factor), then, starting with a single fission, the number of fissions in the nth subsequent generation is just k^n. The average number of neutrons produced by the fission of uranium-235 is around 2.5 and the figure is about 3 for plutonium-239 (Beckett 1983). However, not all these neutrons will go on to cause further fissions, as some will be lost in other kinds of nuclear reaction and some will escape from the fissile material without reacting.

For the purposes of a rough calculation, we can assume a k of 2. The fission of a single uranium-235 nucleus liberates about 3.36×10^{-11} J, whereas around 4.18×10^{12} J is produced by the detonation of 1000 tonnes (a kilotonne) of TNT (a conventional high explosive), so about 1.24×10^{23} uranium-235 fissions yield the same amount of energy as a kilotonne of TNT. You can check with your calculator that the number of fissions in the 77th generation ($n = 77$) exceeds this number for $k = 2$. The time between fission generations is only about 10 nanoseconds, so we can estimate that a nuclear chain reaction in an atom bomb takes around a microsecond from start to finish.

The nuclei of certain light atoms will also fuse together spontaneously with an accompanying release of energy if they approach very close to one another (Figure 5). However, all nuclei are positively charged, so they tend to repel each other. In order to overcome this repulsion, the nuclei require a lot of kinetic energy. The most straightforward way of providing this energy is to heat the material to very high temperatures. It also helps to compress the material, because the nuclei start off closer together and collide due to their thermal motions more frequently at higher densities.

The most favourable fusion reaction for nuclear weapons is that between deuterium and tritium nuclei, which are both 'isotopes' of hydrogen (isotopes have the same number of protons but differ in the number of neutrons). Ordinary hydrogen has just a single proton in its nucleus, whilst deuterium (D) has a proton plus a neutron and tritium (T) has a proton together with two neutrons. The products of the fusion are a helium nucleus, a single free neutron and 2.8×10^{-12} J of energy:

$$^{2}_{1}\mathrm{D} + ^{3}_{1}\mathrm{T} \longrightarrow ^{4}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n} + 2.8 \times 10^{-12}\ \mathrm{J}$$

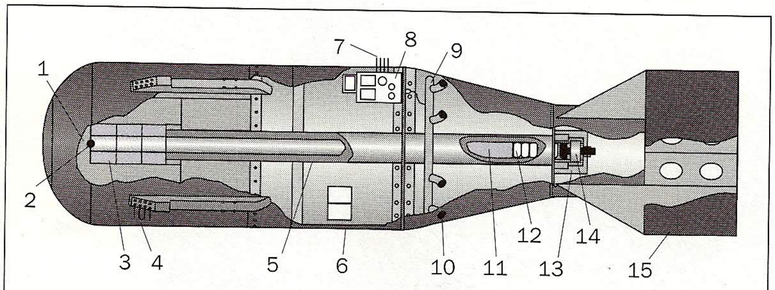


Figure 6 *The* Little Boy *(Hiroshima) bomb.*

ATOMIC BOMBS

If the k factor for a block of fissile material is exactly equal to one, then on average one of the neutrons produced by each fission goes on to cause a further fission and the reaction neither grows nor dies away. A block for which $k = 1$ is called a critical mass and blocks for which k is greater than 1 are said to be super-critical. To create an atomic bomb all that is needed is somehow to assemble very rapidly a super-critical mass of uranium-235 or plutonium-239 and to ensure that there are a few free neutrons around at the same time in order to get the chain reaction going.

One of the most important factors affecting k is the surface area of the block. If a block has a larger surface area relative to the number of fissile atoms which it contains, it tends to have a lower k, because more neutrons are able to escape through the surface.

If you imagine cutting a large block into smaller pieces and moving them apart, then you can visualise that the total surface area of the pieces will be greater than that of the original block, because of the extra area from the cut surfaces. For this reason, if a large block of fissile material is assembled from smaller blocks, it tends to have a larger k value than the parts. It is possible to arrange for a super-critical mass to be assembled from two or more parts, each of which has a k factor less than 1.

This is the principle used in the so-called 'gun assembly' approach, where a bullet of uranium-235 is fired down a barrel into a second sub-critical mass of the same material, thus forming a super-critical mass. The bullet has to approach the target mass at very high speed or the chain reaction has time to start while the bullet is still a little distance away and enough energy could be released to blow the assembly apart before the bullet connected. This premature fission results in a low-yield explosion called a 'fizzle'.

The gun assembly technique was used in the *Little Boy* bomb which was dropped on Hiroshima by the B-29 bomber, *Enola Gay*, on 6 August 1945 (Figure 6). In this device a cylindrical slug of 25.2 kg of uranium-235 was blasted at 300 m s^{-1} down a 7.6 cm diameter barrel into a series of rings made of 34.8 kg of uranium-235 in the nose of the bomb. The yield was 14.5 kilotonnes (Hansen 1988, Beckett 1983, Rhodes 1986).

THE IMPLOSION DESIGN

An implosion is the opposite of an explosion: the blast converges inwards towards a point instead of travelling outwards from it. A spherical implosion can be used to crush a sphere of fissile material so as to reduce its radius, and therefore its surface area, uniformly. The consequential rapid increase in the k factor offers an attractive means of starting a chain reaction, so this has become the most commonly used configuration. Plutonium cannot easily be used in the gun assembly configuration, because the chain reaction is so rapid that there is a high risk of fizzle. However, in the implosion design assembly speeds of around 5000 m s^{-1} are readily achievable (Beckett 1983), so this design is almost always used for plutonium bombs.

In order to implode a sphere of plutonium you might think all you need to do is wrap a layer of explosive around the sphere, place many detonators at evenly spaced points over the outer surface of the explosive and trigger them all simultaneously. However, it turns out that this simply isn't good enough. The main problem is that the ignition waves overlap before they touch the plutonium sphere and where they overlap they reinforce one another, causing the sphere surface to dimple like a golf ball's, allowing the plutonium to jet up between the dimples (Figure 7). The net result may actually be an increase in the surface area of the plutonium. Clearly, a much smoother implosion wave is necessary to maintain the sphericity of the plutonium during its compression.

EXPLOSIVE LENSES

By using a special configuration of different explosives, it is possible to modulate the shape of the convex waves from the detonators to make them concave, so that they fit the surface of the plutonium core precisely. This configuration is called an explosive lens, because it works according to the same principles as an optical lens. A glass lens slows down the light waves as they enter it, and this has the effect of deflecting the wavefront according to the law of refraction. In an explosive lens a block of slow-burn explosive bends the detonation wave at its convex interface with the block of fast-burn explosive in which the detonation is triggered, thus transforming the diverging wave from the detonator into the converging wave required to compress the plutonium core (Figure 8).

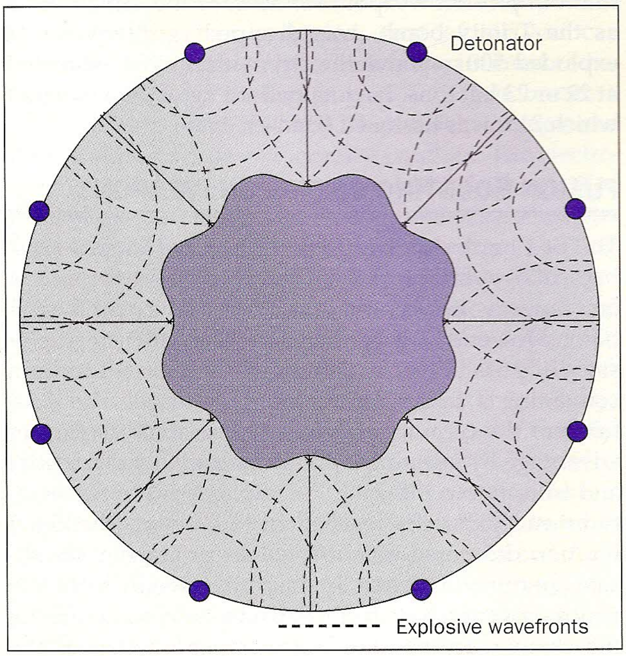


Figure 7 *An imperfect implosion (wavefronts reinforce between detonators).*

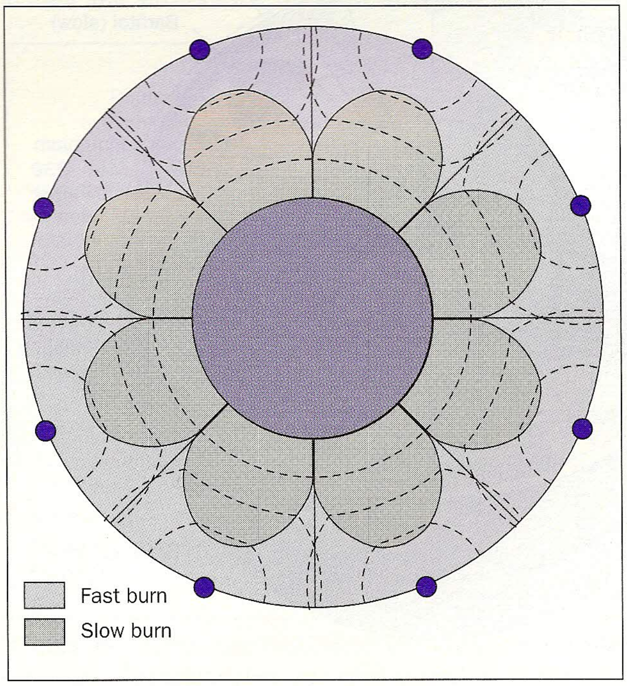


Figure 8 *A perfect implosion using explosive lenses.*

It is known (Rhodes 1986) that the Trinity device used lenses made from three explosive castings (Figure 9) and a total of 96 castings were required. Beckett (1983) describes an 'advanced' device design where the lenses are arranged according to the 20 hexagons and 12 pentagons used to make some soccer balls (Figure 10). Interestingly, 96 = 3 × (20 + 12).

THE TAMPER/REFLECTOR

A fairly thick shell of neutron-reflecting material, called the tamper, surrounds the core in most designs. This needs to be made of atoms which have a low probability of reacting with neutrons from the core, but a high probability of knocking neutrons which hit their nuclei back into the core. This reduces the critical mass by cutting down on the number of neutrons which escape the chain reaction. The tamper can also be designed to help in profiling the detonation wave to ensure that the energy of the implosion is used efficiently to compress the core. Beryllium-9 is the best tamper (it can react with a neutron to emit two neutrons) but another isotope of uranium, uranium-238, also performs adequately and was used in the Trinity device (Rhodes 1986).

THE DRIVER

In some designs the lenses surround a shell of heavy metal (e.g. uranium-238), called the driver. There is an air gap between the driver and the tamper. The implosion accelerates the driver across the air gap, giving it an inexorable momentum, so that the driver compresses the core very rapidly and efficiently. Its inertia also helps to keep the core compressed long enough for the chain reaction to fission a large proportion of the plutonium atoms.

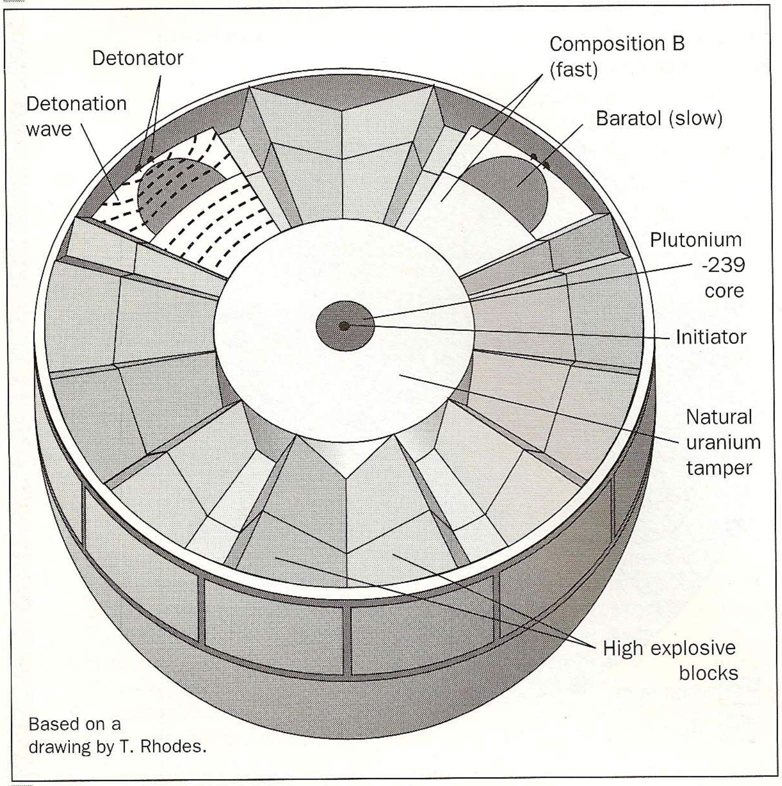


Figure 9 *The Trinity bomb.*

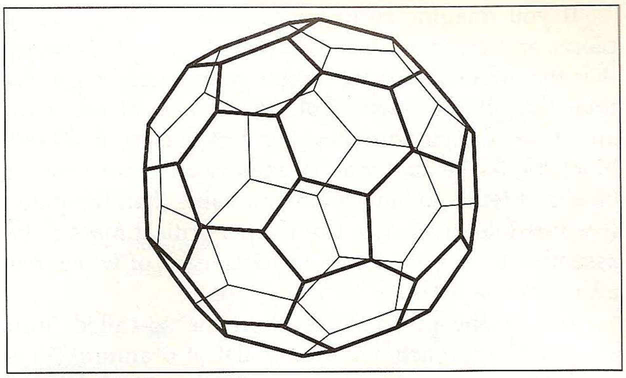


Figure 10 *A truncated icosahedron.*

THE INITIATOR

Although there are usually a few neutrons present in fissile material at any given time, due to occasional spontaneous fissions, for example, it is necessary to be sure that there are plenty of neutrons near the centre of the core at precisely the right moment in order to be sure of initiating an optimal chain reaction. In the Trinity bomb this was achieved by placing a grape-sized device at the centre of the core. This initiator device contained polonium-210 and beryllium separated by metal foils. Polonium-210 is radioactive and emits copious alpha-particles, whilst beryllium emits neutrons when irradiated by alpha-particles. It was arranged that the implosion of the core should break the foils so that alphas from the polonium-210 could reach the beryllium (Rhodes 1986).

More modern bombs are said (Hansen 1988) to use a neutron gun mounted outside the main bomb assembly to fire a burst of neutrons into the core at the right moment.

FAT MAN

At 11.02a.m. on the morning of 9 August 1945 a plutonium implosion weapon, *Fat Man*, of the same design as the Trinity bomb, was dropped on Nagasaki. It exploded 500 m above the city with a yield estimated at 22 or 23 kilotons. It contained 6.2 kg of plutonium of which 21% was fissioned (Hansen 1988).

FUSION BOOSTING OF FISSION WEAPONS

The first implosion weapons reportedly (Rhodes 1986) had solid, spherical plutonium cores about the size of an orange, with a central grape-sized cavity for the initiator. However, a more dramatic and efficient implosion is possible, if a spherical shell of plutonium containing a larger central cavity is used. The existence of the central cavity can be exploited to further advantage by injecting a pressurised mix of deuterium and tritium into it during the implosion. The temperatures and pressures reached in the core as the chain reaction develops are sufficient to produce a significant amount of fusion in this mixture. In turn, the neutrons generated by this fusion help to accelerate the chain reaction, allowing a larger fraction of the core atoms to undergo fission before the assembly blows itself apart.

Figure 11 *Edward Teller, 'father of the hydrogen bomb'.*

HYDROGEN BOMBS

Boosted fission weapons have an upper limit on their yield of about a megaton (1000 kilotonnes). For larger yields, Edward Teller (Figure 11) and a team of US scientists first of all considered various ways of packing more fusion fuel around the outside of an implosion weapon. However, these studies ended in failure in 1950, when computer calculations demonstrated that the fusion fuel would be blown apart before the temperatures and pressures required to ignite it could be achieved. It was not until February 1951 that Stanislaw Ulam (Figure 12) had an interesting idea.

THE RADIATION IMPLOSION

When an iron bar is heated, first of all you can feel heat radiating from it, which is the infrared radiation given out by the hot atoms. As it gets hotter, it starts to glow, first dull red, then bright orange and finally almost white as it becomes molten. The electromagnetic radiation given out by hot objects is called blackbody radiation and it shifts to shorter and shorter wavelengths as the temperature increases. The Sun has a surface temperature of around 6000 K, so its black body radiation is in the visible part of the spectrum, a little hotter than the white-hot iron bar.

The debris in a nuclear explosion is initially much hotter and glows in the X-ray region. These X-rays travel outwards about a hundred times faster than the debris itself (Cladis *et al.* 1971) at nearly the speed of light. They carry around 70% of the energy liberated by the explosion (Glasstone and Dolan 1977), but they are not very penetrating and can be contained for a while by a dense, heavy outer casing. Ulam suggested to Edward Teller that these X-rays might be used to implode and heat a separate capsule of fusion fuel mounted next to the implosion weapon, if both units were contained within the same casing.

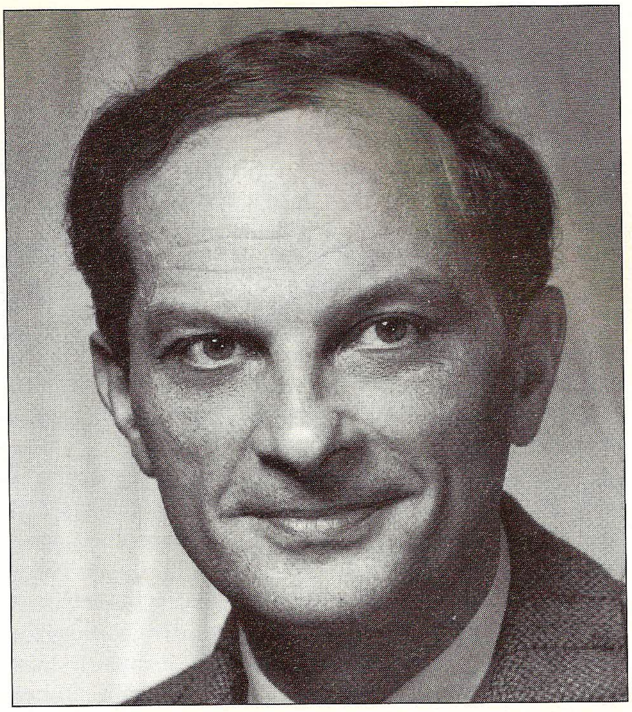
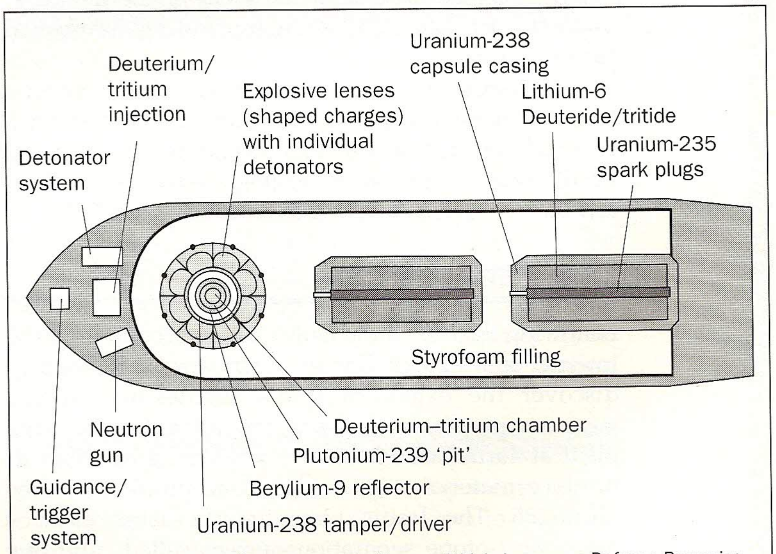


Figure 12 *Stanislaw Ulam, whose idea of using X-rays to implode and heat fusion fuel was a crucial step in the development of the hydrogen bomb.*

THE TELLER–ULAM CONFIGURATION

Ulam's idea turned out to be the crucial breakthrough, though Teller needed to contribute at least one other major innovation before the design became practicable. In its finalised form the invention is known as the Teller–Ulam configuration. Oppenheimer called it 'technically…sweet'. It certainly has a kind of terrible beauty.

A version of this design, which is loosely based on the US Mark 17 device that was the first deliverable hydrogen bomb, is depicted in Figure 13. The containment vessel is cylindrical, but rounded at the end where the plutonium implosion device (called the



Source: British Aerospace Defence Dynamics.

Figure 13 *Three stage thermonuclear weapon according to the Teller–Ulam configuration utilising a radiation implosion (from open sources).*

primary) sits, since this is found to help in scattering the X-ray flash down the tube. This containment vessel is made of some thick, dense metal such as uranium-238. The fusion fuel capsules are also cylindrical and are mounted in styrofoam. The fuel capsules are surrounded by a blanket of uranium-238 (or uranium-235). This blanket is thickened to act as a radiation shield on the side of the capsules facing the primary. The fusion fuel is likely to consist of lithium-6 deuteride and possibly some lithium-6 tritide. These are chemically stable solid compounds of lithium with deuterium and tritium respectively. Lithium-6 has the special property of being readily transformed into helium-4 and tritium, when its nucleus is struck by a neutron:

$$^{6}_{3}\mathrm{Li} + ^{1}_{0}\mathrm{n} \longrightarrow ^{4}_{2}\mathrm{He} + ^{3}_{1}\mathrm{T} + 7.5 \times 10^{-13}\ \mathrm{J}$$

This reaction provides additional tritium for the fusion reaction.

The X-rays from the primary rapidly burn down through the styrofoam, turning it to a high pressure plasma, which compresses the first fuel capsule in a cylindrical implosion. However, the fuel is still not hot enough to undergo fission. This is where the second major design innovation comes in. A cylindrical rod of either uranium-235 or plutonium-239 is located on the axis of the fuel capsule and it is arranged for the cylindrical implosion to send this rod super-critical. A small aperture in the radiation shield allows neutrons from the primary to initiate a chain reaction in the rod, which then supplies neutrons to transmute the lithium into helium and tritium and the extra energy required to spark off the fusion reaction. By analogy with the device used to ignite the fuel in a car engine, this rod is called the 'spark-plug'. The very high energy neutrons released by the fusion reaction are capable of inducing additional fissions in the uranium-238 blanket and the confinement casing. Since each individual fission produces more than ten times the energy of an individual fusion, these fissions can significantly augment the yield of the weapon.

It is possible to extend the yield of the device to virtually any desired value by adding additional fusion capsules.

The first true hydrogen bomb was detonated in a test, codenamed *Mike*, on 1 November 1952 (see back cover). It yielded 10.4 megatonnes and vaporised the Pacific island of Elugelab, leaving a crater 800 m deep and 3000 m wide, which filled with sea water.

IRAQI DEVELOPMENTS

Following the end of the Gulf War, inspectors from the International Atomic Energy Agency were shocked to discover the extent of Iraq's clandestine nuclear weapons programme. There was an industrial scale plant at Tarmiya dedicated to processing uranium to produce material with a high concentration of uranium-235. The Iraqis were mainly using electromagnetic isotope separation devices called calutrons (US Congress Office of Technology Assessment 1993) to enrich uranium in isotope 235.

Calutrons were developed in the USA during World War II and provided the fissile material for the Hiroshima bomb. Iraq obtained massive technical support for its programme from Western industry under various false pretences: for example, the magnet core castings for its calutrons were supplied by a European foundry. The Iraqis acquired sophisticated, computer-controlled machine tools that could be used for the precision milling of explosive lenses or bomb cores. They were also found to possess flash X-ray photography facilities and high-speed streak cameras, useful for studying the timing and compression in spherical implosion assemblies.

MORALITY

Nuclear weapons can be used to do good — for instance, by destroying or deflecting an asteroid which threatens to collide with the Earth — as well as evil. It is my personal view that their possession by the UK is an important guarantee of our freedom and security. However, in the hands of irresponsible people nuclear weapons present a great threat to the future well-being of the world. An improved awareness and vigilance among scientists is one of the ways in which this threat may be countered. ■

Andrew Chugg is a member of the Radiation Effects Group of British Aerospace Dynamics Division at Filton, Bristol. He is responsible for research and development activities relating to protecting space and defence systems from harsh radiation environments.

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